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RESEARCH MEMORANDUM

TURBOJET ENGINE INVESTIGATION OF EFFECT OF THERMAL SHOCK INDUCED BY EXTERNAL WATER-SPRAY COOLING ON TURBINE BLADES OF FIVE HIGH-TEMPERATURE ALLOYS

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

The thermal-shock effect of water-spray impingement upon turbine rotor blades subjected to rated engine operating conditions was determined in an investigation of external water-spray cooling. A centrifugal-compressor engine, modified to permit water injection from orifices in the rotor blade bases and from stationary orifices in the stator, was employed.

The engine was operated at rated speed (11,500 rpm) and a turbine inlet-gas temperature of 1625° F. Turbine-blade cooling water was turned on and off in cycles which employed either sudden or gradual injection of cooling water. A total equivalent coolant-to-gas flow ratio of 0.032 through both the stationary and rotating injection system was maintained to provide uniform cooling over the entire turbine blade surface.

The S-816 test blades withstood 40 cycles with sudden water injection without cracking while subjected to a centrifugal stress of 25,700 pounds per square inch at the blade root. Cracks along the blade trailing edges and in some cases along the leading edges appeared after 20 cycles with the Nimonic 80 blades, after 11 cycles with the Inconel X blades, and after 9 cycles with the HS-21 blades. The Guy alloy blades failed at the first application of water sprays. Gradual water injection did not improve thermal-shock test results.

INTRODUCTION

External water-spray cooling of gas-turbine blades as a means of permitting short periods of increased thrust operation is being investigated at the NACA Lewis laboratory. The phase of the investigation reported herein deals with the heat-shock effect of introducing water to the blade surfaces at conditions of high blade stress and blade temperature.

The mechanism of the spray cooling process and the gains in thrust possible with spray cooling are considered analytically in reference 1. Experimental verification of this analysis is provided by the tests reported in reference 2 which showed a 20-percent increase in rated thrust at 107 percent rated speed and a 2000° F inlet-gas temperature with a centrifugal-compressor engine modified for spray cooling. The problem of nonuniform blade spray coverage which caused failure-inducing blade-temperature differences is considered in references 1, 3, and 4. A water-injection configuration was evolved which resulted in virtually constant temperatures over the entire blade surface (ref. 4). In order to facilitate these investigations, however, the blade-thermal-shock aspect was deliberately minimized by turning on the water sprays simultaneously with the engine starts.

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The investigation reported herein was initiated to determine whether turbine blades subjected to high centrifugal stress and inlet-gas temperatures could withstand the thermal shock induced by the repeated impingement of water sprays. The single-stage turbine of a centrifugal-compressor turbojet engine was modified to provide the most effective water-injection configuration as determined in reference 4. This configuration consisted of water-injection orifices in the rotor blade bases and stationary injection orifices in the stator diaphragm. Cyclic operation generally consisting of 2 minutes at an 0.032 total equivalent coolant-to-gas flow ratio (equivalent flow rate of about 17 gal/min) and 5 minutes without spray cooling was conducted at rated engine speed and a 1625° F turbine inlet-gas temperature until blade failure was encountered. Test blades of five high-temperature turbine blade alloys were employed.

APPARATUS

Turbine Blades

Fifty unmodified production blades of S-816 material and four test blades comprised the complete turbine rotor and blade assembly. The four test blades were of the same profile as the production blades and were modified to include five water-injection orifices in the base as shown in figure 1. The injection orifices were 0.031 inch in diameter and were located along the suction surface. Test blades of two alloys (two of one alloy and two of another) were always installed for any period of cyclic operation. Test blades were made of five high-temperature alloys. The alloys investigated were wrought S-816, Nimonic 80, Inconel X, cast HS-21, and cast Guy alloy. The first four alloys were chosen because they are commonly used in aircraft turbine blades and the thermal-shock effect of spray cooling on such blades should be known in order to evaluate aircraft application of turbine spray cooling. Guy alloy, although not commonly used, shows promise for high-temperature, high-stress applications and was therefore included.

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Engine Modifications

The engine used in this investigation was a production turbojet engine that was modified to permit water-spray cooling of the turbine rotor blades. Two water-spray systems were employed simultaneously with the test blades. The details of both systems are given in reference 4, but a brief description of each is presented herein.

Rotating injection system. - The rotating injection configuration employed in this investigation was one that provided nearly uniform cooling of the blade when used in conjunction with the proper stationary injection configuration (ref. 4). Various components of the rotating injection system are illustrated in figure 2 and the design details are described in reference 4. The four test blades provided with injection orifices in the blade base were spaced at approximately 90° intervals around the rim of the turbine disk. Water was supplied to a stationary manifold (fig. 2) through stainless steel tubing and discharged to the rotating gutter on the rear face of the rotor. The water then flowed radially through four liquid-transfer tubes, which were fastened to the rotor rear face, and into axial passages in the rotor rim directly beneath each of the test blades. The maximum water flow rate for any rotative speed was established by the metering action of 0.015-inch-diameter flow-control orifices located in plugs force-fitted into the rotor above the rotor axial passages. Centrifugal force on the water permitted it to bridge the slight clearance space between the rotor and blades. Water then flowed through the drilled passages in the rotor blade base and onto the blade surface through the injection orifices. In order to minimize the possibility of clogging the small flow-control orifices, distilled water was used in the rotating injection system.

Stationary injection system. - Both the location and the size of the stationary injection orifices were the same as those that provided the most uniform blade temperature distribution in conjunction with the rotating injection orifices of reference 4. The stationary injection system was similar to that employed in reference 2. Figure 2 illustrates the location of one of the stationary orifices in the inner ring of the stator nozzle diaphragm. Two orifices, 0.200 inch in diameter, located 180° apart on the inner ring of the stator diaphragm, were employed. Because of the relatively large diameter of these orifices, the probability of clogging was not great and city water was employed in the stationary injection system.

Instrumentation

The general engine instrumentation is described in detail in reference 2. Engine air flow, fuel flow, speed, and tail-pipe gas temperature were measured. In order to avoid slotting the blade surfaces and weakening the blades, no thermocouples were installed on the turbine blades. Separate rotameters were used to measure the rates of water flow through the rotating and stationary injection systems.

PROCEDURE

All engine operation was conducted at sea-level ambient conditions. In order to subject the turbine rotor blades to thermal shocks similar to those encountered in a spray-cooled aircraft engine, a cyclic type of operation utilizing both water-injection systems was employed. First the engine was brought to rated speed (11,500 rpm) and a turbine inlet-gas temperature of about 1625° F. Then water was introduced to the rotor blades simultaneously through both the stationary and rotating injection orifices. Similarly, in an aircraft installation, once the engine had reached full power, spray cooling would be applied to obtain the added thrust necessary for combat or maneuver.

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For the first type of cyclic operation (sudden injection) reported herein, 4 seconds were required to bring the cooling-water flow rate from zero to the maximum rate desired. Injection of water was continued for 2 minutes, and then the flow was reduced from the maximum rate to zero flow in 4 seconds. Then followed 5 minutes of uncooled engine operation at rated conditions, after which the entire procedure was repeated. The second type of cyclic operation (gradual injection) differed in the time required to introduce and shut off the water flow. In this type of cycle, 30 seconds were required to bring the water flow rate from zero to maximum. Injection was continued at the maximum flow rate for 2 minutes, and then the flow was reduced to zero in 30 seconds. There followed 4 minutes of uncooled operation at rated engine conditions, after which the entire procedure was repeated. In both types of cycle the maximum flow rate was equal to a total equivalent coolant-to-gas flow ratio of 0.032. The term equivalent coolant-to-gas flow ratio is employed in order to evaluate flow rates through the rotating injection system with respect to the flow rates through the stationary injection system. Only the four test blades were cooled with the former system; therefore, the actual flow values were much less than those for an entire set of cooled blades. The stationary system cooled the entire set of blades. Consequently, an equivalent flow equal to that required for cooling the entire set of blades with the rotating injection system was used in computing total coolant-to-gas flow ratio. The total equivalent coolant-to-gas flow ratio of 0.032 was required to provide uniform chordwise blade temperature distributions for this turbine, as demonstrated in reference 4. In order to minimize blade chordwise temperature differences, the rotating-system equivalent flow rate was maintained at twice that of the stationary system (ref. 4).

All the test blades were subjected to the sudden-injection type of cyclic operation. Test blades of two alloys, HS-21 and Inconel X, were also subjected to gradual-injection operation. Two test blades of one alloy and two of another were investigated during any period of cyclic operation. Test blades were given X-ray and Zyglo inspection prior to installation. Zyglo inspection of the test blades as well as of several

of the blades cooled only by the stationary injection system was made after approximately every 10 cycles. If the examination showed evidence of cracks, the blades were not tested further. If inspection revealed no cracks, the blades were reinstalled in the engine and operation was continued for another 10 cycles. A total of 40 cycles was arbitrarily selected as being representative for a military aircraft spray-cooling installation, assuming one application per mission, and this figure was set as a limit for the test blades. The remaining blades (unmodified for injection through the blade bases) were left in the engine throughout the entire test unless Zyglo inspection revealed cracks.

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The procedure followed in this investigation did not entirely duplicate an aircraft spray-cooling application. In order to minimize mechanical difficulties with other parts of the engine, the turbine speed and inlet-gas temperature were not raised above rated once the coolant was introduced. The effect that the added stresses imposed by higher operating speeds would have on blade life is not known, although figure 8 of reference 2 indicates a substantial margin of safety between the allowable stress for the cooled condition and the operating stress for 107 percent rated speed. As stated previously, the water sprays were turned on and off at rated engine speed and a 1625° F turbine inlet-gas temperature; thus, the engine operating conditions at the instant of water injection and shut-off were similar to those that would occur in an aircraft spray-cooling application for the engine investigated. Consequently, the procedures employed herein are considered valid in determining whether or not spray cooling can be applied without causing immediate thermal-shock blade failures. The present investigation does not attempt to determine the long-range effect of these shocks on blade life. This is another factor that should be considered before the practicability of spray cooling can be assured.

RESULTS AND DISCUSSION

A summary of the results obtained with both types of cyclic operation is presented in table I.

Results with Blades Modified for Rotating Injection

Tests with sudden water injection. - As shown in table I, only one of the five blade alloys investigated, S-816, showed no failure cracks after 40 cycles of operation with sudden water injection. Three blade alloys, Nimonic 80, Inconel X, and HS-21, withstood fewer cycles before cracks were initiated. Cracks in the trailing edge, between the 2/3 and 3/4 span position, were observed after 20, 11, and 9 cycles, respectively, with these blades. In the case of the Inconel X blades, similar cracks were observed at the leading edge at about the same spanwise position.

Figure 3 shows an HS-21 blade after 9 cycles. The trailing-edge cracks illustrated in this figure are typical of all those encountered. The fifth blade material, Guy alloy, failed immediately upon introduction of the water during the first cycle. Figure 4 shows the root section of a failed Guy alloy blade. Failure occurred at the blade root section in both Guy alloy test blades. The generally brittle nature of the material probably played a major role in this result. X-ray examination of these Guy alloy blades prior to operation indicated casting imperfections in one blade that may also have contributed to the blade failures.

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Tests with gradual water injection. - Two of the blade materials, HS-21 and Inconel X, were investigated under conditions of gradual water injection as a means of reducing the thermal-shock effect. The test blades of these materials had cracks similar to (and in one case even more pronounced than) cracks in the blades investigated under conditions of sudden water injection. Figure 5 shows an HS-21 blade after 10 cycles with gradual water injection. The cracks occurred at about the same spanwise position as on one of the HS-21 blades tested with sudden water injection. The Inconel X blades both showed a pronounced crack at the leading edge as well as smaller cracks at the trailing edge after 10 cycles. Figure 6 shows one of the Inconel X blades after 10 cycles utilizing gradual water injection. A large crack at the leading edge, approximately at the 2/3-span position is clearly visible. A similar crack was observed on the other Inconel X test blade. Slight trailing-edge cracks were observed but are not apparent in this figure. Comparison of these results with those for sudden water injection indicates that no improvement in blade life resulted for HS-21 and Inconel X blades, and further tests with gradual water injection were abandoned.

Results with Blades Unmodified for Rotating Injection

No cracks were observed in the standard rotor blades, which were made of S-816 alloy. These blades remained in the rotor during all the sudden-water-injection cycles (40) and all the gradual-water-injection cycles (10). Since these blades were cooled only by the stationary injection system, large chordwise temperature differences were imposed in the tip region (ref. 2) while there was a maximum water flow rate. These temperature differences did not occur in the blades modified for rotating injection (ref. 4), so the unmodified blades were actually subjected to a more severe test. The total of 50 cycles without a failure under these conditions further points out the usefulness of S-816 blades in spray-cooling applications. Although these blades satisfactorily withstood the thermal-shock aspect of water injection from stationary orifices, there is an undesirable effect on blade life due to prolonged operation with large chordwise temperature differences at the blade tip (ref. 2). As a consequence, the life of these blades should not be as long as that of the test blades that were cooled by both the rotating and stationary injection systems.

GENERAL COMMENTS

The foremost result of the present investigation is that a current-production-alloy (S-816) turbine blade can withstand the repeated sudden impingement of water sprays without cracking while subjected to high centrifugal stress. Another factor should be considered, however, particularly with regard to the blade materials that showed cracks after fewer cycles. The blade centrifugal stress in this investigation was 25,700 pounds per square inch at the blade root, probably as high a stress level as current design practice considers feasible for uncooled blades. At a lower centrifugal stress the effect of thermal stresses induced by water impingement would probably not be as disastrous. Consequently, the other blade materials investigated may prove to be satisfactory for spray-cooling applications in lower-stressed turbine blades. It should also be noted that changes in the heat treatment of these blades may provide more satisfactory resistance to thermal shocks.

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SUMMARY OF RESULTS

The results of an investigation to determine whether turbine blades subjected to high centrifugal stress (25,700 psi) at the blade root and high gas temperature (1625° F) can withstand thermal shock induced by the repeated impingement of water sprays are as follows:

1. Blades made of S-816 material withstood 40 cycles of operation with sudden water injection without cracking.

2. Cracks appeared along the blade trailing edges and in some cases along the leading edges after 20 cycles with Nimonic 80 blades, after 11 cycles with Inconel X blades, and after 9 cycles with HS-21 blades. Guy alloy blades failed at the first application of water sprays.

3. The use of gradual water injection did not improve thermal-shock test results.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 17, 1955

REFERENCES

1. Freche, John C., and Stelpflug, William J.: Investigation of Water-Spray Cooling of Turbine Blades in a Turbojet Engine. NACA RM E53A23, 1953.

2. Freche, John C., and McKinnon, Roy A.: Investigation of Turbojet Engine Performance at Speeds and Gas Temperatures Above Rated Using Turbine-Blade External Water-Spray Cooling from Stationary Injection Orifices. NACA RM E54G30, 1954.

3. Freche, John C., and McKinnon, Roy A.: Experimental Investigation of Several Water-Injection Configurations for Turbine-Blade Spray Cooling in a Turbojet Engine. NACA RM E53H06, 1953.

4. McKinnon, Roy A., and Freche, John C.: Experimental Investigation of External Water-Spray Cooling in a Turbojet Engine Utilizing Several Injection Configurations Including Orifices in the Rotor-Blade Bases. NACA RM E54K29a, 1955.

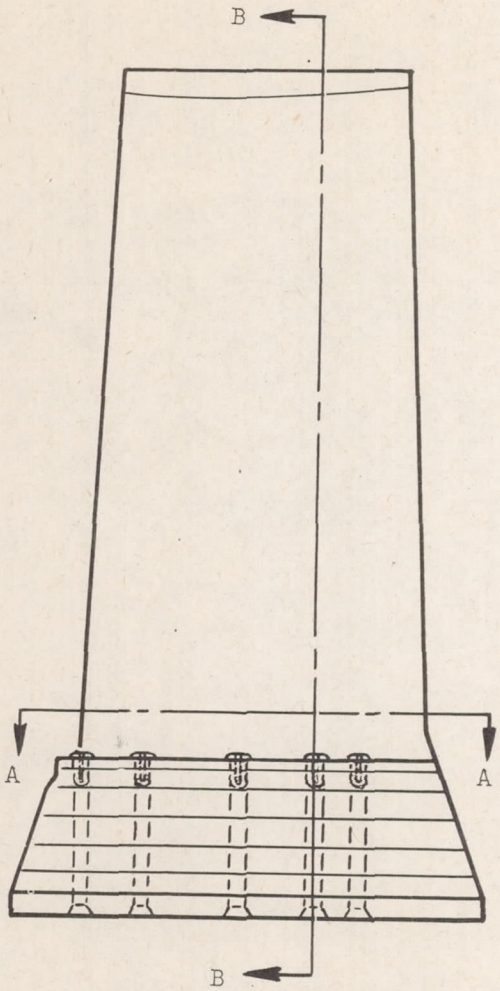
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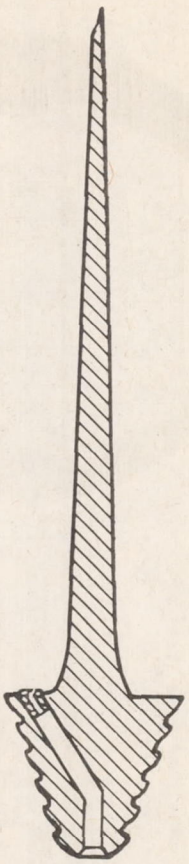
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TABLE I. - SUMMARY OF THERMAL-SHOCK TESTS

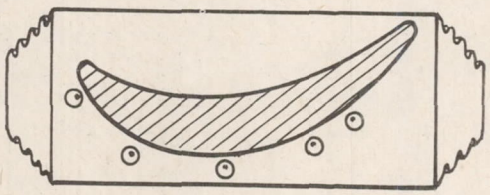
Blade material	Engine speed, rpm	Turbine inlet-gas temperature, °F	Type of cycle	Number of cycles before blade damage	Results
S-816	11,500	1625	Sudden water injection	40	No blade damage
Nimonic 80				20	Trailing-edge cracks at 2/3 and 3/4 span
Inconel X				11	Trailing- and leading-edge cracks at 3/4 span
HS-21				9	Trailing-edge cracks at 2/3 and 3/4 span
Guy alloy				0	Blades failed at base immediately upon introduction of water
Inconel X			Gradual water injection	10	Trailing- and leading-edge cracks at 2/3 span
HS-21				10	Trailing-edge cracks at 3/4 span

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Section B-B



Section A-A

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Figure 1. - Turbine rotor blade modified for water injection.

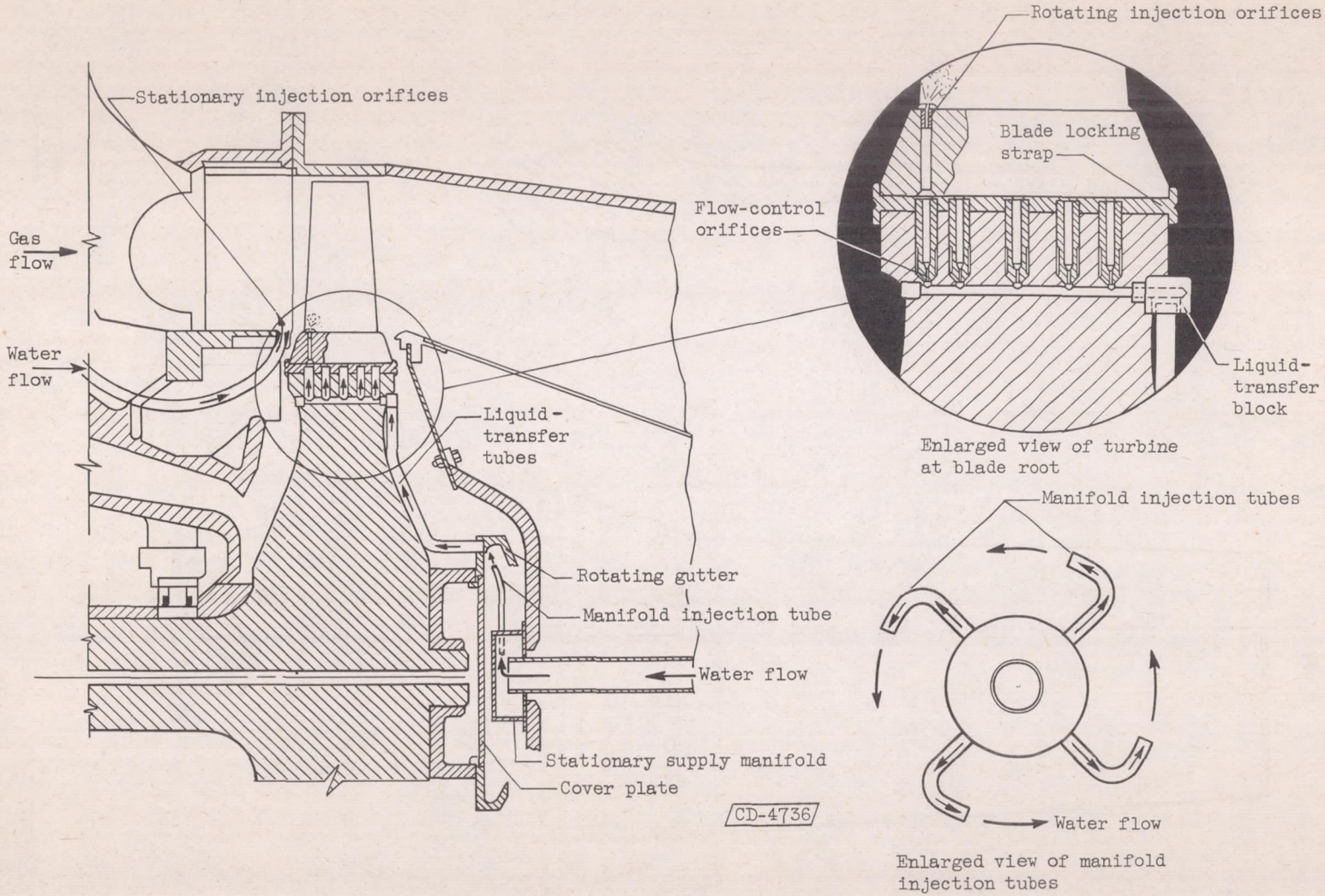


Figure 2. - Sectional view of engine showing ducts for water-spray injection from orifices located in turbine rotor blade bases and from stationary orifices in stator diaphragm.

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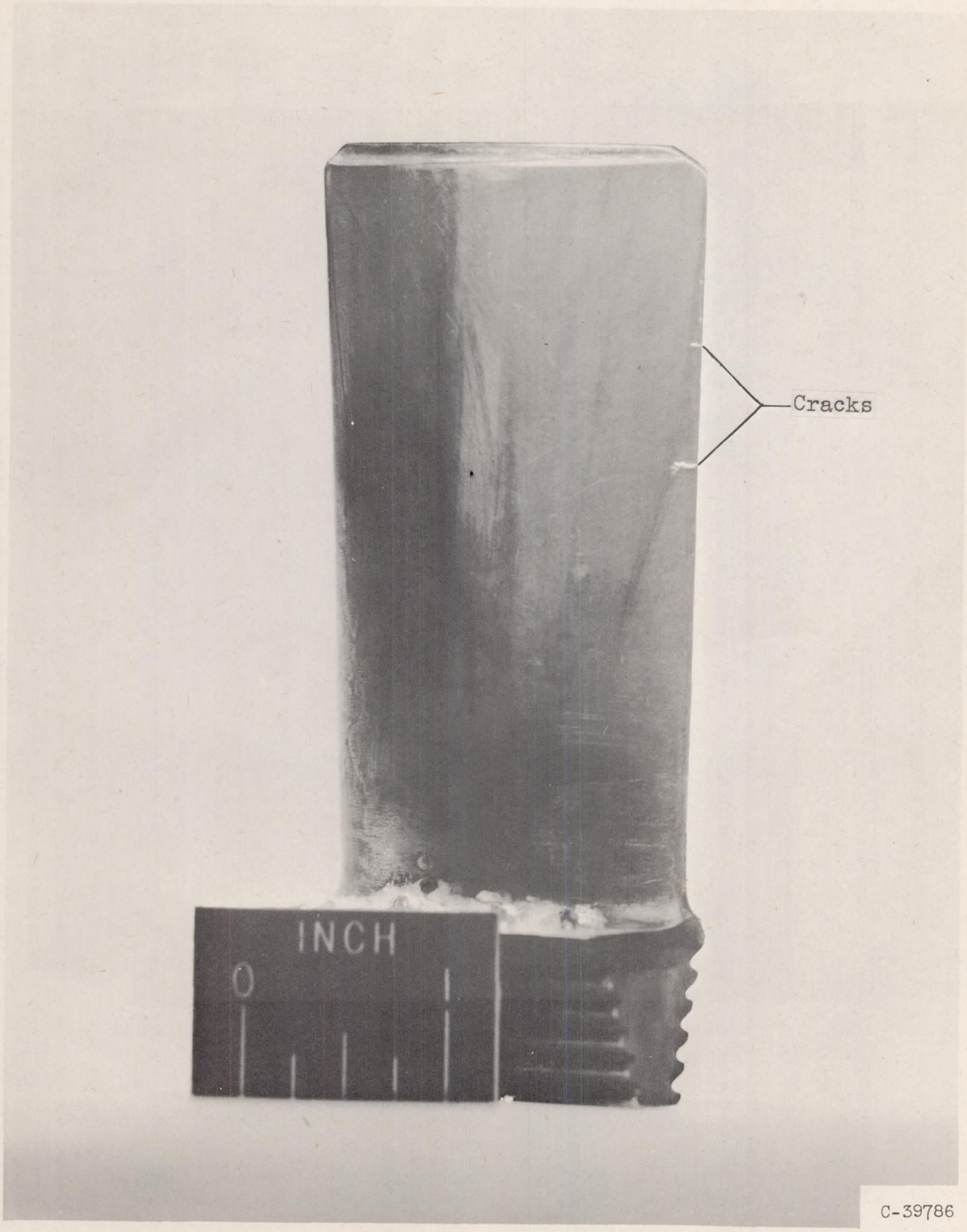


Figure 3. - HS-21 spray-cooled turbine blade with cracks in trailing edges after nine cycles of operation with sudden water injection.

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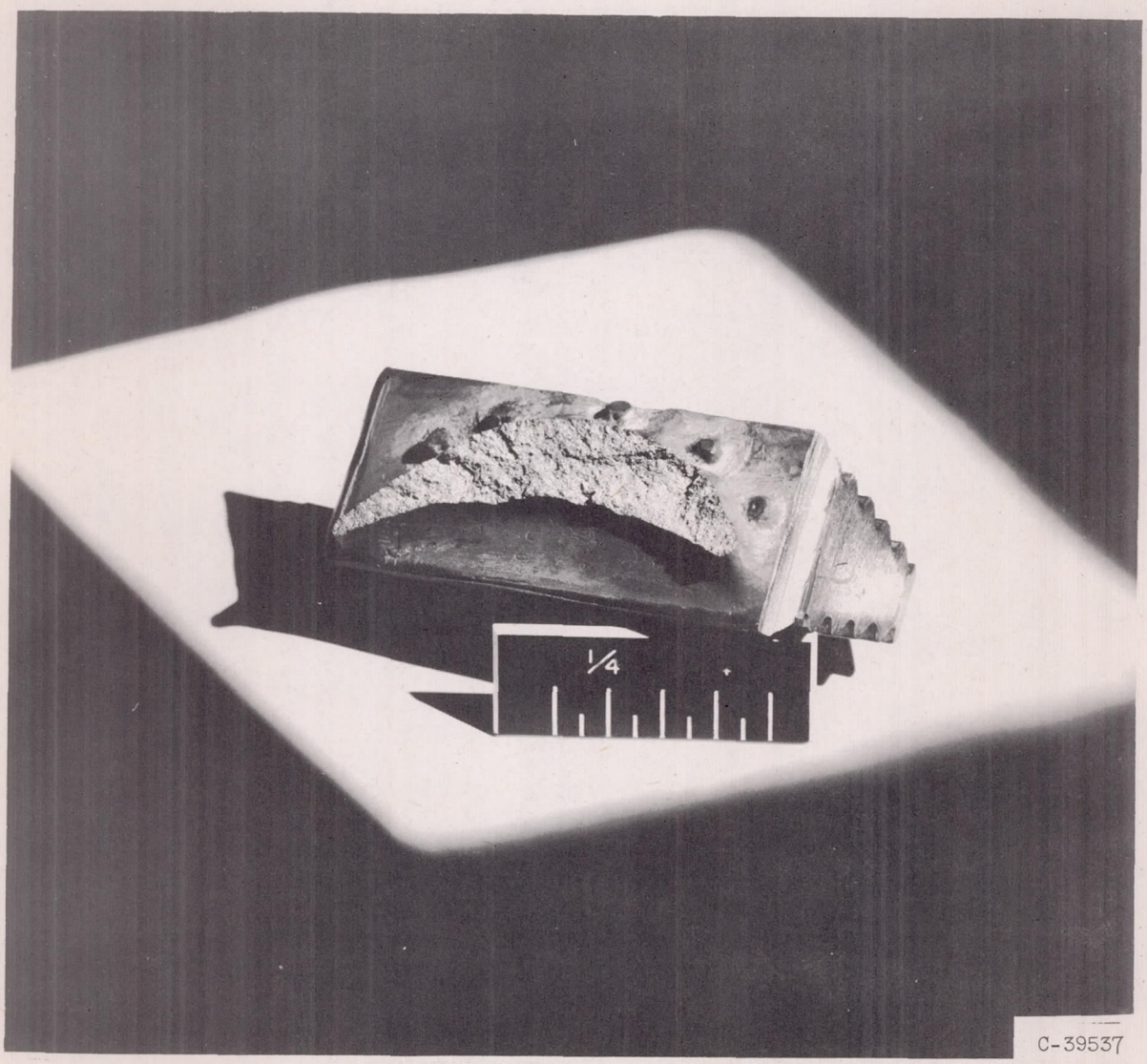


Figure 4. - Root section of Guy alloy spray-cooled turbine blade that failed immediately upon injection of water.

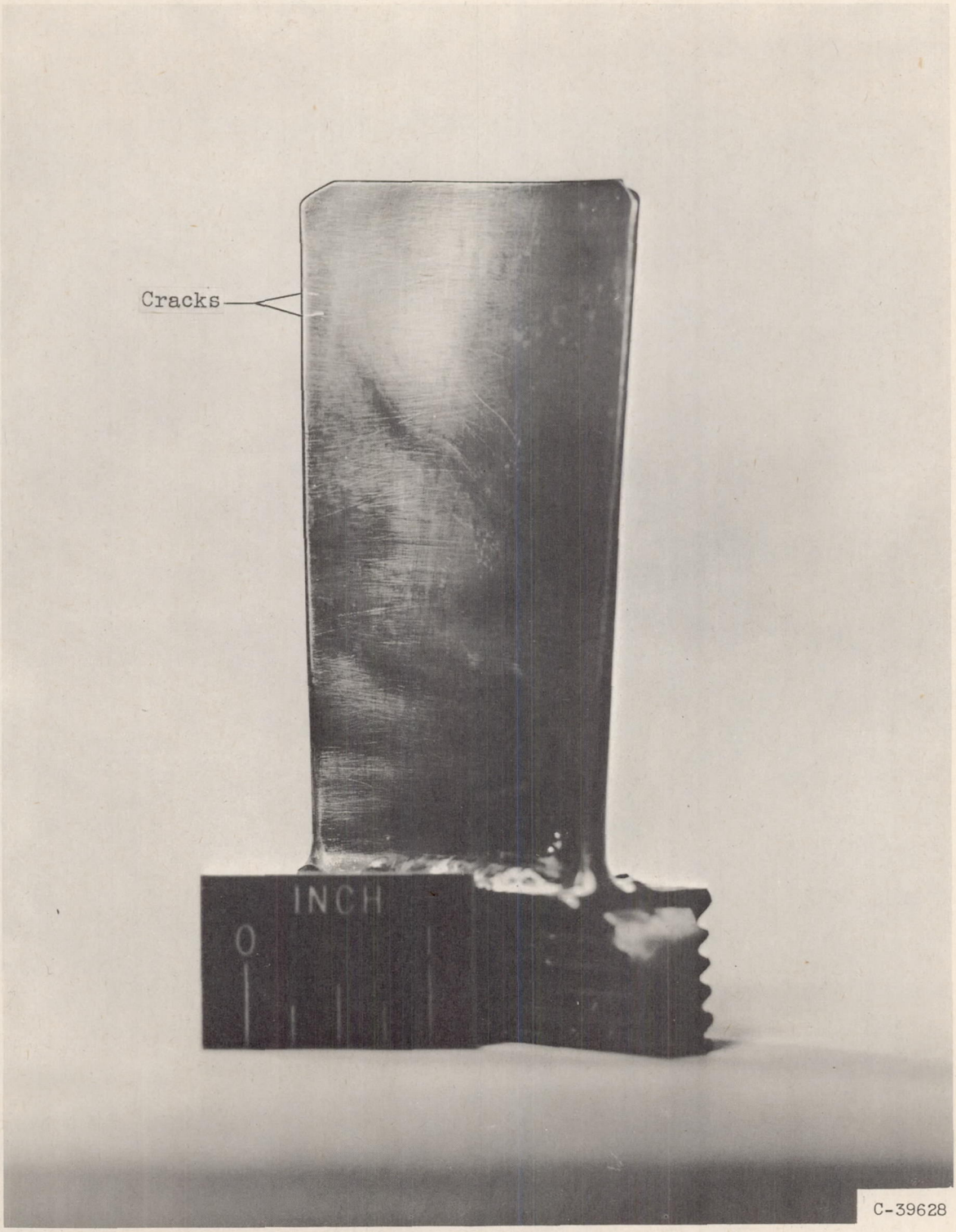


Figure 5. - HS-21 spray-cooled turbine blade with cracks in trailing edge after 10 cycles of operation with gradual water injection.



Figure 6. - Inconel X spray-cooled blade with crack in leading edge after 10 cycles of operation with gradual water injection.